Project Title

Stephen Busch
Organization: Sandia National Laboratories
Address: PO Box 969, MS 9053
Livermore, CA 94551-0969
Phone: (925) 294-2216
E-mail: sbusch@sandia.gov

Gurpreet Singh, DOE Program Manager
U.S. Department of Energy
Phone: (202) 586-2333
E-mail: Gurpreet.Singh@ee.doe.gov

Start Date: 10/01/2016 End Date: 9/30/2017
Total Project Cost: $885k DOE share: $885k Non-DOE share: $0

Project Introduction

Despite compliance issues in previous years, automakers have demonstrated that the newest generation of diesel power trains are capable of meeting all federal and state regulations (EPA, 2016). Diesels continue to be a cost-effective, efficient, powerful propulsion source for many light- and medium-duty vehicle applications (Martec, 2016). Even modest reductions in the fuel consumption of light- and medium duty diesel vehicles in the U.S. will eliminate millions of tons of CO_2 emissions per year. Continued improvement of diesel combustion systems will play an important role in reducing fleet fuel consumption, but these improvements will require an unprecedented scientific understanding of how changes in engine design and calibration affect the mixture preparation, combustion, and pollutant formation processes that take place inside the cylinder. The focus of this year's research is to provide insight into the physical mechanisms responsible for improved thermal efficiency observed with a stepped-lip piston. Understanding how piston design can influence efficiency will help engineers develop and optimize new diesel combustion systems.

Objectives

- Provide the physical understanding of the in-cylinder combustion processes needed to minimize the fuel consumption and the carbon footprint of automotive diesel engines while maintaining compliance with emissions standards and meeting customer expectations
- Develop efficient, accurate computational models that enable numerical optimization and design of fuel-efficient, clean engines
- Provide accurate data obtained under well-controlled and characterized conditions to validate new models and to guide optimization efforts

Approach

The overall research approach involves carefully coordinated experimental, modeling, and simulation efforts. Detailed optical measurements of flow, mixture preparation, and combustion processes are made in an optical research engine facility based on a General Motors 1.9-liter automotive diesel engine. Careful attention is also paid to obtaining accurate boundary conditions to facilitate comparisons with simulations, including intake flow rate and thermodynamic properties; and wall temperatures. The engine geometry and experimental data are made publically available (Busch, 2017). These data support commercial code vendors' efforts to develop and evaluate numerical simulation tools that will be used to design and optimize the next generation of clean, efficient diesel combustion systems.

Close collaboration with numerical simulation experts at the University of Wisconsin-Madison (subcontractors) provides a much-needed compliment to the optical engine experiments. The experimental results guide the development of advanced numerical models and enable the evaluation of computational simulations. In turn, analysis of the simulation results generates a deeper understanding of in-cylinder flow and combustion physics. The results of this combined approach are not possible to obtain with experimental data alone, and the analyses provide fundamental, science-based understanding of mechanisms that increase thermal efficiency or influence tradeoffs between efficiency, emissions, and combustion noise. Publication of this knowledge helps guide the development and calibration of advanced diesel engines.

Results

Key accomplishments:

- Identified improvement of the degree of constant volume combustion as a key to improving thermal efficiency.
- Demonstrated that engine efficiency improves with a stepped-lip piston compared to with a conventional piston, because the second half of combustion occurs faster and the degrees of constant volume combustion is therefore higher.
- Analyzed numerical simulation results to reveal the mechanism by which the stepped-lip piston changes turbulent flow structure and enhances mixing.

Last year's experimental results demonstrated that a stepped-lip piston bowl can improve thermal efficiency by several percent and reduce smoke emissions by half, compared to a conventional, re-entrant piston bowl. These improvements depend on injection timing, but are generally in agreement with other results found in the literature. This year, research efforts have been devoted to understanding the physical mechanism responsible for the improvement in thermal efficiency. Two prevalent theories for the efficiency improvement are found in the literature. The first is that heat loss through the combustion chamber walls may be reduced with the stepped-lip piston, so that more energy is available to do mechanical work. The second theory is that the stepped-lip piston enhances mixing-controlled combustion rates, so that more work can be extracted from the combustion products during the expansion stroke. The extent to which either of these factors contributes to the improvement in thermal efficiency has not yet been demonstrated.

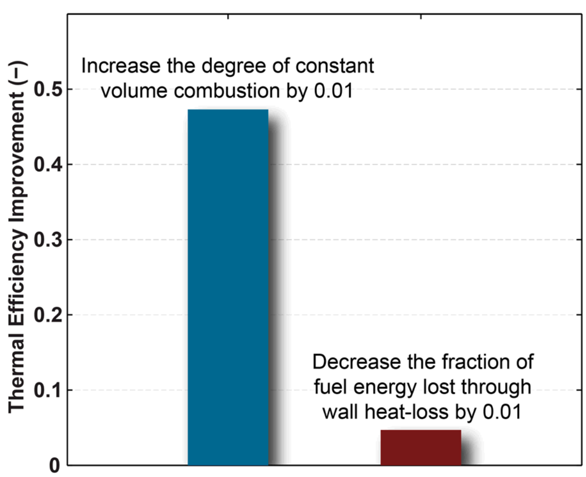

Figure 1: In a diesel engine, increasing the work extracted by the piston is significantly more effective at improving thermal efficiency than reducing the amount of energy lost through the combustion chamber walls.

A simple thermodynamic model has been constructed to test both of these theories. Artificially generated heat release profiles are model inputs, and the model computes the cylinder pressure and the net amount of work extracted for the given amount of heat input. Variations in the heat-release phasing and duration change the degree of constant volume combustion. The degree of constant volume combustion (dCVC) is a measure of how closely the heat release profile mimics an idealized, constant-volume heat release at top dead center (TDC). A late, slow combustion event will result in a low value of dCVC, whereas rapid combustion near TDC will result in a value of dCVC closer to one. Wall heat-loss is simulated using a commonly used algebraic model, and the ratio of the total amount of heat-loss throughout the cycle to the total heat input is computed as a metric for comparison.

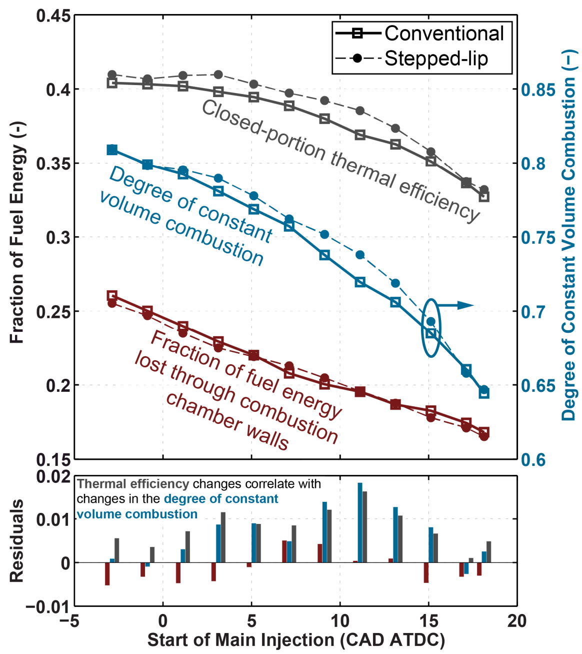

Figure 2: Thermal efficiency (the fraction of fuel energy extracted as work) is higher with the stepped-lip piston for some injection timings. The efficiency differences correlate with differences in the degree of constant volume combustion. Wall heat loss does not change with piston bowl geometry in a significant way.

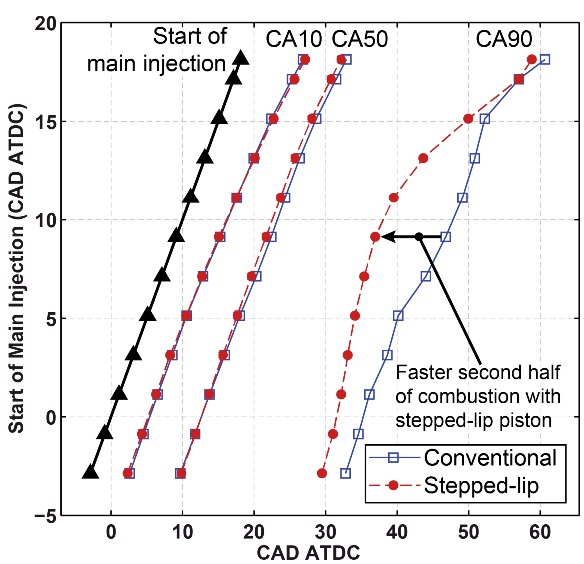

Figure 3: as the main injection timing is delayed, the combustion takes place later in the expansion stroke. Piston bowl geometry does not affect the first half of the combustion event (until CA50), but the second half of combustion is faster with the stepped-lip piston.

Figure 1 compares the efficiency improvement resulting from a small increase in dCVC with the efficiency improvement resulting from a comparatively small decrease in wall heat-loss. Increasing the degree of constant volume combustion is more effective at increasing thermal efficiency than decreasing the amount of wall heat-loss. This is true for a wide range of main injection timings.

Experimental data are processed to estimate thermal efficiency, the degree of constant volume combustion, and wall heat-loss for both the conventional and the stepped-lip piston geometries. These results are shown in Figure 2 for a range of main injection timings. The efficiency improvements are most significant for main injections starting between 3 crank angle degrees after TDC (CAD ATDC) and 13 CAD ATDC. The residual plots shown in Figure 2 demonstrate that total estimated wall heat-loss is not strongly affected by this change in piston bowl geometry. Furthermore, the efficiency improvements are strongly correlated with the change in dCVC, but not with the change in wall heat-loss. This result, together with the theoretical consideration shown in Figure 1, suggests that increasing the degree of constant volume combustion is an effective way to improve the thermal efficiency of direct injection diesel engines.

Data found in the literature suggest that stepped-lip pistons enhance rates of combustion during the second half of the combustion event, and analysis of the experimental data in the project confirms this finding. The crank angles at which 10, 50, and 90% of the fuel energy has been released (CA10, CA50, and CA90, respectively) are shown for a range of injection timings for both piston geometries in Figure 3. CA10 and CA50 are affected by injection timing, but only to a very small extent by piston geometry. The effect of piston geometry is most evident after CA50: the duration between CA50 and CA90 is shorter by as much as 10 CAD with the stepped-lip piston. At an engine speed of 1500 rpm, CA90 is achieved approximately 1 ms faster than with the conventional piston. This results in a higher degree of constant volume combustion and therefore in higher thermal efficiency with the stepped-lip piston. Because turbulent mixing processes in the cylinder control this second half of the main heat release event, changes to turbulent flow and mixing are fundamental to the mechanism of increasing efficiency with the stepped-lip piston.

While ongoing experimental efforts to characterize the turbulent flow structure in the engine may provide further insight into the role of piston geometry in increasing efficiency, computational fluid dynamics (CFD) simulations are necessary to provide a more complete picture of this complex, dynamic, three-dimensional phenomenon. CFD capabilities at the University of Wisconsin-Madison have been developed to simulate flow, the fuel injection, mixing, and combustion on a model of the whole engine, including the intake system, the cylinder, and the exhaust system. Past work has been devoted to evaluating the code's ability to predict the flow in the cylinder, and the results have shown differences in the flow fields simulated with the conventional and the stepped-lip piston geometries (Perini, 2017). This year predictions of the liquid and vapor fuel spray behavior have been compared with experimental data. A comparison of fuel vapor concentrations is shown in Figure 4 for the conventional piston bowl geometry. The data have been measured and/or computed in three horizontal planes, which are depicted at the bottom of Figure 4.

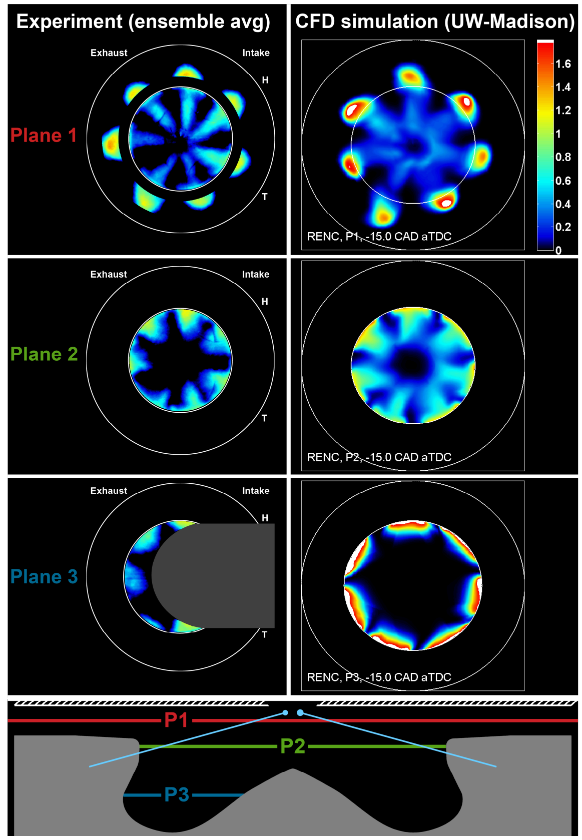

Figure 4: Comparison between fuel vapor concentrations measured experimentally by planar, laser-induced fluorescence of a fuel tracer (left), and fuel vapor concentration predicted by the CFD simulation (right). Results are shown in false-color for three horizontal cutting planes for the conventional bowl geometry (depicted at the bottom). The latest simulation results reliably predict vapor penetration above and into the piston bowl, as well as jet deflection by the swirling in-cylinder flow.

The comparisons indicate reliable prediction of fuel jet behavior with the full engine computational domain and the state-of-the-art spray models employed at the University of Wisconsin. The results shown in Figure 4 are a dramatic improvement compared to previous approaches, in which only a sector of the cylinder was simulated. The penetration rate of the jets, the gradients in fuel concentration, and the degree of penetration down into the bowl match more closely with experimental data than ever before. The deflections of the jets as they exchange momentum with the swirling in-cylinder flow are also well predicted. Simulation results compare favorably with experimental results for both piston geometries. The goal at this stage of the project is not 100% quantitative agreement between simulation and experiment, but reliable qualitative prediction of the phenomena associated with fuel injection, spray, and mixing processes.

The comparisons between experimental data and simulation results did not reveal any significant deficiencies in the modeling and simulation approaches, so the simulation results are used to provide insight into how piston bowl geometry interacts with the fuel injection to influence turbulent flow structure during and after the main injection. Figure 5 shows a comparison between vertical-plane flow structures at two crank angles for the conventional piston (left) and the stepped-lip piston (right). This simulation is performed for a main injection starting at 9.1 CAD ATDC, so differences in turbulent flow structure may be expected to appear after the experimentally determined value of CA50 of approximately 22 CAD ATDC (see Figure 3), or at 12.9 CAD $ASOI_m$. The top row of images shows what is happening shortly before CA50, and the bottom row of images depicts the evolution of the flow and mixing.

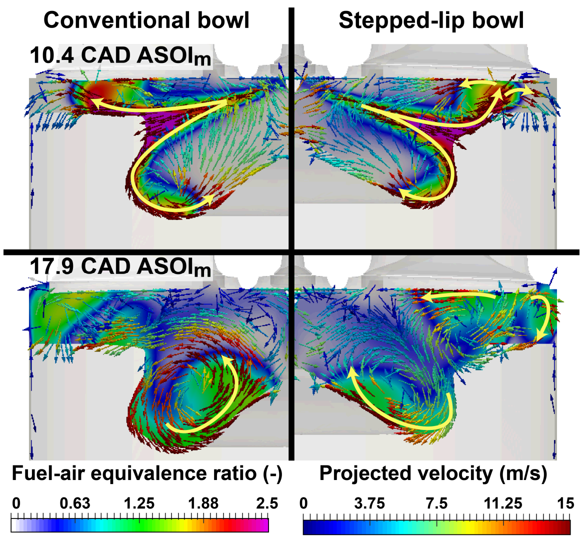

Figure 5: Simulated vertical-plane projection of flow fields (shown with colored vectors) and the fuel concentrations (false-colored field data) for the conventional (left) and stepped-lip (right) pistons. Yellow arrows have been added to indicate the motion of the fuel jets. Crank angles are shown in CAD after the start of the main injection ($ASOI_m$).

With the conventional bowl, a significant portion of the jet impacts on or below the vertical bowl rim, and is redirected down into the bowl. This reinforces the prevailing flow in the cylinder and results in the formation of a vertical-plane vortex structure, called a toroidal vortex (see second row, first column of Figure 5). The toroidal vortex is energetic and long-lived; it contains the majority of the fuel and is the predominant flow feature for the conventional bowl. The uppermost portion of the fuel jet does not interact with the bowl, but instead continues to propagate outward into the so-called squish region. The outwardly propagating jet impinges on the cylinder wall, and much of this fuel remains in the outer portion of the squish region.

As expected, the interaction between the fuel jets and the stepped-lip piston geometry produces a different flow structure than with the conventional piston. A toroidal vortex forms in the lower portion of the stepped-lip bowl, but it is smaller and less pronounced than with the conventional bowl. Differences in the flow structure above the piston begin to appear even before CA50, as seen in the first row of Figure 5. The portion of the jet that impinges on the sloped step surface is deflected outward along the step and upward at the outer bowl rim. It forms a secondary jet that propagates upward and impinges on the cylinder head. This second impingement results in spreading of fuel-air mixture and turbulence, and in the formation of two additional recirculation zones (see the second row, right column of Figure 5). One recirculation zone forms in the outermost portion of the cylinder, while the other forms above the step. Both act to transport fuel-air mixture and turbulence to regions with excess oxygen, which is believed to be the reason for enhanced combustion rates and improved thermal efficiency with the stepped-lip piston.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Conclusions

Investigations with a conventional, re-entrant piston bowl and a stepped-lip piston bowl demonstrate that the stepped-lip piston can improve thermal efficiency by several percent, and the focus of this year's research was to generate a deeper understanding of the mechanism responsible for the efficiency improvement. Thermodynamic analyses, validation of CFD simulations with data from optical experiments, and analysis of the CFD results reveals the following:

- Increasing the degree of constant volume combustion is more effective than reducing wall heat loss to improve thermal efficiency.
- Changing from the conventional piston to the stepped-lip piston results in a small change in estimated wall heat-loss, and the changes in wall heat loss have an insignificant impact on thermal efficiency.
- The degree of constant volume combustion is higher for injection timings with improved efficiency with the stepped-lip piston; dCVC correlates strongly with thermal efficiency.
- Higher degrees of constant volume combustion with the stepped-lip piston are the result of enhanced heat release rates during the second half of combustion.
- Interactions between the fuel sprays and the stepped-lip piston bowl result in the spreading of mixture and turbulence, which likely increases the rate of combustion and thereby the thermal efficiency.

References

Busch, S., “Small-Bore Diesel Engine.” Accessed 11/8/2017. https://ecn.sandia.gov/engines/engine-facilities/small-bore-diesel-engine/.

Perini, F., Zha, K., Busch, S., Kurtz, E., Peterson, R., Warey, A., Reitz, R., “Piston geometry effects in a light-duty, swirl-supported diesel engine: flow structure characterization.” International Journal of Engine Research, accepted for publication October 2, 2017.

The Martec Group, “Diesel engine technology and the midterm evaluation: An analysis of compliance costs and benefits.” Accessed online July 10, 2017: http://www.martecgroup.com/wp-content/uploads/2016/05/The-Martec-Group-White-Paper-Diesel-Engine-Technology-and-the-Midterm-Evaluation-Summer-2016.pdf

US EPA, “Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation: Technical Support Document.” Document EPA-420-R-16-021, November 2016.

Key Fiscal Year 2017 Publications

1. Park, C. and Busch, S., "The influence of pilot injection on high-temperature ignition processes and early flame structure in a high-speed direct injection diesel engine," International Journal of Engine Research, DOI: 10.1177/1468087417728630

Acronyms, Abbreviations, Symbols, & Units

ASOIm	after the start of main injection
ATDC	after top dead center
CAD	crank angle degrees
CFD	computational fluid dynamics
dCVC	degree of constant volume combustion
TDC	top dead center